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Applied Energy 83 (2006) 774–788

APPLIED ENERGY

www.elsevier.com/locate/apenergy

Tubular guidance systems for daylight: Achieved and predicted installation performances

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Available online 18 October 2005

Abstract

Tubular daylight-guidance systems are linear devices that channel daylight into the core of a building. The development, over the last decade, of materials with high specular reflectance has led to a large number of passive zenithal systems; the most commercially successful type of daylight guidance being installed in many parts of the world. The rapid change in technology has not been matched by the development of either reliable and standardised design methods or design criteria against which the systems may be evaluated. This paper presents the results of several surveys of daylight guidance systems in 13 working buildings. These give an indication of the conditions created, which are used as the bases of suggested design criteria. A critical review of existing performance prediction methods notes that these lag far behind comparable methods for electric lighting and conventional glazing. A number of improved methods of prediction, currently under consideration by the CIE Technical Committee TC3-38, are presented and each is tested against measured data from the installation surveys.

Keywords: Daylight; Daylight guidance; Design; Prediction; Measurement; Light pipes

1. Introduction

Tubular daylight guidance systems are linear devices that channel daylight into the core of a building. The development, over the last decade, of materials with high specular reflectances has led to a large number of passive zenithal systems; the most commercially

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0306-2619/$ - see front matter
doi:10.1016/j.apenergy.2005.08.001

successful type of daylight guidance, being installed in many parts of the world. Passive zenithal tubular daylight-guidance systems consist of a clear polycarbonate dome that accepts sunlight and skylight from part or the whole sky hemisphere, a rigid or flexible tube lined with highly reflective silvered or prismatic material to redirect the light, and light output devices, commonly diffusers made of opal or prismatic material or an array of Fresnel lenses.

The largest market for passive zenithal daylight-guidance is that of the technically unsophisticated user owned, domestic buildings where, typically, a single guide lights a living or ancillary space. Systems are now being installed in office, industrial and health-care buildings, where they contribute to the lighting of a working interior. In these applications, a good visual environment for employees is a major factor in satisfying requirements, including statutory regulations, for a safe and productive workplace. Unfortunately, the rapid change in light-delivery technology has not been matched by the development of either reliable and standardised design methods, or design criteria against which the systems may be evaluated in the context of the building and its lighting installation. This lack of authoritative design guidance may lead to few of the potential benefits of the systems, in terms of energy saving and user comfort in working buildings, being realised.

Despite the popularity of the systems, published information on the performance of systems is scarce. This paper reports surveys of achieved conditions in a number of installations in working buildings and these were related to characteristics of the building and its lighting system. This feedback on some of the ‘first generation’ daylight-guidance systems gives an indication of conditions created by the systems in practice. These results are used as the basis for suggested design criteria and appropriate metrics for specification.

There has been research effort to devise methods of predicting performance of systems or individual components throughout the development of tubular daylight guidance. Initially, this was concentrated on light transport devices, but latterly a range of methods of predicting light delivery and/or distribution within a building’s interior has been put forward. These range from semi-empirical methods to those based on ray tracing, but none is presently configured for routine design use. Most address a limited range of design issues (guide configurations or sky conditions for example) and testing has been limited to a small number of (usually theoretical) data sets. Taken together, the lack of design criteria and the limitations of the prediction methods mean that daylight guidance suffers by comparison with electric lighting and conventional glazing. Both of these have long established standard methods of production of design data and means of evaluation of alternative lighting schemes. To address this deficiency, the CIE Technical Committee TC3-38 is developing both methods of photometry and prediction that overcome many of the disadvantages encountered to date. This paper reviews the various prediction methods that have been promulgated and describes and identifies those that are both capable of acknowledging design criteria and are suitable for routine design use. The methods are tested against the data from the results of the surveys of installations.

2. Daylight-guidance prediction methods

This section describes methods of prediction of illuminance (within a building) from guidance systems. It is not concerned with the designs of the components of these systems. Any method of prediction must address:

- Assumptions about prevailing sky-condition and external illuminance at the collector.
- The efficiency of the guide in delivering light to the interior.
- The distribution of light exiting the output devices.

Methods developed over the last decade differ in the ways in which the above are addressed and whether they are computer- or paper-based methods. All of the methods described are in the public domain and are freely available.

2.1. Existing methods

The Luxplot package is a semi-empirical method based on measurements, at different times of the year, on actual installations at a variety of sites throughout the UK [1,2]. The guides measured ranged in diameter from 0.3 to 0.53 m, in length from 0.6 to 6 m and guide bend angles from 5° to 75°. External conditions are represented by global illuminance irrespective of sky condition. The authors' work suggested that, while a given global illuminance from a winter clear-sky might not produce exactly the same internal illuminance as the same global illuminance from summer cloudy conditions, the difference is so small as not to require separate models. Inputs are external illuminance, guide and bend configurations, and floor plan with guide and internal illuminance calculation locations. The model calculates the luminous flux exiting the guide complete with diffuser and estimates the light distribution at points below the ceiling diffuser using a cosine illuminance relationship. This is displayed as a graded "colour-luxplot" across a two-dimensional horizontal plane, average floor illuminance and average daylight factor.

The Zhang and Muneer [3] method is a semi-empirical method based on measurements on actual installations and is intended for use with guides with "opal" diffusers. The sky model used requires solar altitude and sky clearness parameters as inputs, since the incidence angle of light entering the pipe will affect guide transmittance. Two separate models for straight and elbowed light guides are, therefore, capable of distinguishing between the magnitude of light available and the direction(s) of the incoming light. As a result, the predictions are season or time-of-day specific as well as estimate average annual performance. The method puts forward the daylight penetration factor (DPF) to describe the guide performance. This is analogous to the daylight factor (DF) used for conventional windows except that the global exterior illuminance is used as the basis of the calculation.

SkyVision software, written by the National Research Council of Canada, predicts daylight performance for sky wells and conventional skylights as well as light guides and may also assess the supplementary electric lighting required to attain a target illuminance [4]. The input comprises room details including surface reflectance, position of up to 50 light guides per room, guide length and diameter, and guide and output device reflectance and transmittance. An in-built database includes glazing properties and a range of sky models including the CIE overcast-sky model and clear-skies that include global illuminance values for different calendar and diurnal times. The output, presented as graphs or tables, gives the average floor-illuminance and/or daylight factor across a specified area rather than for specific positions in the room.

The University of Liverpool semi-empirical method treats a light guide for calculation purposes as a luminaire using an estimated or measured flux emitted by a guide and its luminous intensity distribution [5]. The method is based on measurements for guides of diameters 0.33. 0.45 and 0.53 m and lengths of 0.6 and 1.2 m with opal diffusers. The flux

input is based on external illuminance measurement. Flux exiting the guide is either measured by a photometric integrator, or estimated using the nadir illuminance and the "zone factor" method for symmetric luminaires described in CIBSE TM5 [6] using a measured luminous intensity curve for an opal diffuser; the results of the two methods differing by less than 10%.

This enables estimates of the overall guide efficiency to be made. Knowing the luminous flux emission and luminous-intensity distribution, a number of methods of calculation of illuminance distribution in a given room are possible. A "point-by-point" hand calculation, based on the inverse square/cosine law of illuminance, can be used. Alternatively a 'lumen method' calculation based on a utilization factor (UF) may be used to estimate the average work-plane illuminance from a uniform array of guide output devices. For this method, the output devices are considered to be flush mounted luminaires for which UF values are obtained from the literature [7]. The method accounts for the effects of guide bends with suggested losses and is in approximate agreement with the studies of Jenkins and Muneer. The method may also be used with general-purpose lighting analysis software in which a guide output device is treated as a luminaire using the measured luminous-intensity distribution and estimated flux output. An example using Lumen Micro 2000 is described in [8].

2.2. CIE guide transmission efficiency method

CIE Technical Committee TC3-38 has proposed both a method of photometry, and a prediction method for output device efficiency for collectors, straight guides and those with bends. The prediction method, based on 'tube-transmission efficiency' (TTE), is founded on fundamental physical principles and has been extensively tested against results from photometry measurements. For a guide of given optical equivalent length and diameter the TTE is calculated as follows:

$$\mathrm{TTE} = \mathrm{e}^{c}/(1-c)^{0.5} \quad \text{and } c = \mathrm{AR} \times \tan Z \times \log R,$$

where AR is the aspect ratio (L/D); L is the equivalent optical-length (m); D is the diameter (m); R is the specular reflectance of the mirrored inner-surface of the guide; Z is the portion of the zenithal overcast-sky from which illuminance enters the guide.

This equation gives realistic values for overcast-sky conditions, assuming $Z = 30°$. The example in Table 1 shows TTE values for guides lined with 99.5% specular-reflectance material.

The method permits the evaluation of the performance of a wide range of configurations of passive guide-systems, including the influence of bends and is used as follows.

Allowance is made for any bends in the proposed guide configuration. Determining the equivalent length of straight guide that will have similar optical losses to the bend does this. This varies with bend configuration and examples are shown in Table 2. These values are added to those of the straight lengths. Table 1 gives the TTE for the total length of the guide.

If T_c is the transmittance of the collecting dome, T_o is the transmittance of the output device and MF is the maintenance factor, then:

Overall guide efficiency $E_g = \mathrm{TTE} \times T_c \times T_o \times \mathrm{MF}$.

Knowing the guide area A and external global illuminance E_h, then the total flux entering the guide $F_e = E_h \times A$.

Table 1
TTE values for guides lined with 90.5% specular-reflectance material

Length	Diameter (m)									
	0.25		0.375		0.53		0.65		0.9	
	TTE	L/D	TTE	L/D	TTE	L/D	TTE	L/D	TTE	L/D
0.25	1	1	1	0.67	1	0.47	1	0.38	1	0.28
0.5	0.99	2	0.99	1.33	1	0.94	1	0.77	1	0.56
1	0.98	4	0.99	2.67	0.99	1.89	0.99	1.54	1	1.11
2	0.97	8	0.98	5.33	0.98	3.77	0.99	3.08	0.99	2.22
3	0.95	12	0.97	8.00	0.98	5.66	0.98	4.62	0.97	3.33
4	0.93	16	0.95	10.67	0.97	7.55	0.97	6.15	0.98	4.44
5	0.92	20	0.94	13.33	0.96	9.43	0.97	7.69	0.98	5.56
6	0.9	24	0.93	16.00	0.95	11.32	0.96	9.23	0.97	6.67
8	0.87	32	0.91	21.33	0.94	15.09	0.95	12.31	0.96	8.89
10	0.84	40	0.89	26.67	0.92	18.87	0.94	15.38	0.95	11.11
12	0.82	48	0.87	32.00	0.91	22.64	0.92	18.46	0.94	13.33
14	0.79	56	0.85	37.33	0.89	26.42	0.91	21.54	0.94	15.56
15	0.78	60	0.84	40.00	0.89	28.30	0.91	23.08	0.93	16.67

Table 2
Equivalent straight guide length having similar optical losses to a bend (m)

Bend angle	Guide diameter (m)			
	0.25	0.375	0.53	0.65
30°	1.2	1.3	1.2	1.0
60°	2.4	2.4	2.1	1.8
90°	3.2	3.1	2.7	2.4

Total flux emerging from the output device $F_i = F_e \times E_g$.

The final step is to analyse the distribution of light within the interior. The most usual requirement is for some average illuminance or DPF across the working plane.The method used to do this is the utilization factor [6,7]. This is based on the determination of the total flux reaching the work plane, comprising a component coming direct from the output device and an indirect component reflected via the room's surfaces. Assuming the output devices are dished or flush ceiling mounted with no upward luminous flux, the utilization factors for the work plane are shown in Table 3. Similar values are available for floors or walls.

Thus, the average working plane DPF for an installation with N guides is

$$DPF = (N \times F_i \times \mathrm{UF})/(A \times E_h)\%.$$

2.3. Discussion of prediction methods

It is perhaps worth considering the choices currently available to a designer wishing to use daylight-guidance systems. Although he may possess some knowledge of the possible collector location, guide routeing, permissible diameter and length, output device location, size of room and prevailing sky type, there are no design criteria on which to base any form of comparison between alternative systems. The designer can either rely on

Table 3
Utilisation factors for arrays of dished or flush output devices

Room index	Effective ceiling reflectance (%)	Reflectance of floor or working plane = 10%. Reflectance of wall				Reflectance of floor or working plane = 30%. Reflectance of wall			
		50%	30%	10%	0	50%	30%	10%	0
0.8	70	0.51	0.43	0.37	0.34	0.54	0.44	0.37	0.35
	50	0.49	0.42	0.36	0.34	0.52	0.43	0.37	0.35
	30	0.48	0.41	0.36	0.34	0.50	0.42	0.37	0.34
1.0	70	0.57	0.49	0.43	0.40	0.61	0.51	0.44	0.41
	50	0.55	0.48	0.42	0.40	0.58	0.50	0.43	0.41
	30	0.54	0.47	0.42	0.40	0.56	0.49	0.43	0.40
1.25	70	0.63	0.55	0.49	0.46	0.68	0.59	0.51	0.48
	50	0.61	0.54	0.49	0.46	0.65	0.57	0.50	0.47
	30	0.59	0.53	0.48	0.46	0.62	0.55	0.49	0.47
1.5	70	0.68	0.60	0.54	0.52	0.74	0.64	0.57	0.54
	50	0.66	0.59	0.54	0.51	0.70	0.62	0.56	0.53
	30	0.64	0.58	0.53	0.51	0.67	0.60	0.54	0.52
2.0	70	0.75	0.68	0.62	0.59	0.83	0.74	0.66	0.63
	50	0.72	0.66	0.61	0.59	0.78	0.70	0.64	0.61
	30	0.70	0.65	0.60	0.58	0.74	0.68	0.62	0.60
3.0	70	0.83	0.77	0.72	0.70	0.93	0.85	0.79	0.76
	50	0.80	0.75	0.71	0.69	0.87	0.81	0.75	0.73
	30	0.78	0.74	0.70	0.68	0.82	0.77	0.73	0.70
4.0	70	0.88	0.83	0.78	0.76	0.99	0.92	0.86	0.84
	50	0.85	0.81	0.77	0.75	0.93	0.87	0.83	0.80
	30	0.83	0.79	0.76	0.74	0.87	0.83	0.79	0.77

manufacturers' assurances or do a comparison himself. The difficulty with the former is that each manufacturer uses different system components and each has their own methods of stating system performance, usually one driven by commercial concerns. This makes any comparison between manufacturers' offerings difficult. The other alternative is to use one of the tools described in Section 2.1. These range from theoretical and empirical based 'hand calculation' to fully developed computer-software packages. The utility of semi-empirical methods could be constrained by the limited range of measurements on which they are based. In practice, however, all commercial systems are made up of components that are similar, both physically and optically, so they are more widely representative than might first appear. Whilst the methods can cope with a number of sky types, the evidence is that this is unnecessary. Of more concern is the necessity to incorporate the methods into computer software (given that this is unlikely to be economic to a practising designer) and the lack of standardised testing or comparison of the methods. The Skyvision package, although not yet fully commercially supported, is capable of handling a variety of sky types and standard components, but its output is limited to averages over specified areas. None of the methods, except the Liverpool method used in conjunction

with lighting software, is capable of simultaneously handling windows in their daylight analysis and all are limited to rectangular plan rooms.

The CIE method is a hand-calculation method based on tabulated data and is configured to be usable by both specialist lighting designers and the large number of non-specialists who are the major customer base for light guides. The method is based on theoretical principles, but has been tested against data from the CIE photometry method. It permits evaluation of alternative designs from different manufacturers based on a standard test method. It is capable of investigating systems that may incorporate all common types of component and material optical properties.

3. The surveys

The 13 buildings in the study were located in the UK and details are shown in Table 4. The installations were mainly in commercial, healthcare or academic buildings, in which clerical or similar work was undertaken. Five of the installations were in new buildings, but most were retrofitted to existing accommodation.

Exterior and interior views of two installations are shown in Fig. 1. All were equipped with electric lighting in addition to guided daylight. The electric lighting was almost exclusively mirrored louvered downlighters with tubular or compact fluorescent lamps. Eight of the installations were windowless, the others having vertical windows as described in Table 4. The guide output devices were circular domed or flat opal diffusers, or 600 mm $\times$ 600 mm square lensed panels, all located in suspended ceilings. Two installations had daylight linked continuously to variable electric-lighting. A further site had an individual luminaire control, but the majority of the sites had no additional control of electric lighting.

Visits to all buildings were made during the period November 2001–July 2004. Photometric measurements were mainly made in conditions of winter daylight, but some, including second visits to Buildings 1–4, were made in summer conditions. Since the surveys took place in working areas, the data-collection methods were necessarily limited to those that did not interfere with the running of the organisation. Each survey commenced with an interview with a facilities manager: information was collected on the nature and use of the building, design specification for hardware and controls/software, maintenance and system configuration. Detailed information on room layout, lighting layout and control, window and blind details is summarised in Table 4. A single illuminance measurement was made in the centre of the working area at each workstation first for a combination of electric lighting and daylight and second, if possible, for daylight only.

3.1. Results

3.1.1. Facilities-management issues

Only installations 1 and 2 had any form of daylight linking installed, but on both visits, this system was disabled. The effect of this was that the lighting levels in all installations varied upwards from the electric-lighting design illuminance. There was no evidence of systematic maintenance in any installation despite evident problems of condensation and dirt accumulation inside some guides. The mode of usage of the systems was that of an electric system with conventional on–off switching. In no installations had staff received information on system use, and anecdotal evidence suggested that knowledge of the guidance systems amongst users was sparse.

Table 4
Summary of installations

Building type	Size (m) *Room index*	Output device details[a]	Electric lighting (lamp colour)	Windows[b]	Output device luminance (cd/sq.m.)	Daylight control[c]
1.1. Office Phase 1	9.5 × 5.2 × 2.7 *1.76*	6 no. Manu A flush diffuser 450 mm diameter	8 no. 600 × 600 mm mirrored downlight	2 no. 0.6 × 2.0. Sill height 0.7 green Venetian blinds	2600 nadir 580–1100 from seated position	Daylight linking disabled
1.2. Office Phase 2	9.5 × 5.2 × 2.7 *1.76*	6 no. Manu A flush diffuser 450 mm diameter	8 no. 600 × 600 mm mirrored downlight	2 no. 0.6 × 2.0. Sill height 0.7 green Venetian blinds	5000 nadir 3000–5000 from seated position	Daylight linking disabled
2.1. Office Phase 1	14.5 × 11.5 × 2.7 *3.3*	15 no. Manu A flush diffuser 450 mm diameter	24 no. 600 × 600 mm mirrored downlight	5 no. 0.6 × 2.0. Sill height 0.7 green Venetian blinds	3600 nadir	Daylight linking disabled
2.2. Office Phase 2	14.5 × 11.5 × 2.7 *3.3*	15 no. Manu A flush diffuser 450 mm diameter	24 no. 600 × 600 mm mirrored downlight	5 no. 0.6 × 2.0 Sill height 0.7 green Venetian blinds	8200 nadir 4200–7000 from seated position	Daylight linking disabled
3.1. Conference room Phase 1	9.7 × 5.9 × 2.2 *2.6*	6 no. Manu A domed diffuser 330 mm diameter	7 no. 1200 × 600 mm prismatic panels	None	850 nadir 600–700 from seated position	None
3.2. Conference room Phase 2	9.7 × 5.9 × 2.2 *2.6*	6 no. Manu A domed diffuser 330 mm diameter	7 no. 1200 × 600 mm prismatic panels	None	9000 nadir 6000–10000 from seated position	None
4.1. Office/electrical workshop Phase 1	21 × 9 × 2.6 *3.5*	8 no. Manu A flush diffuser 450 mm diameter	38 no. 600 × 600 mm prismatic panels (CW)	None	3800 nadir 1200 from seated position	PD only

(*continued on next page*)

Table 4 (*continued*)

Building type	Size (m) *Room index*	Output device details[a]	Electric lighting (lamp colour)	Windows[b]	Output device luminance (cd/sq.m.)	Daylight control[c]
4.2. Office/ electrical workshop Phase 2	$21 \times 9 \times 2.6$ *3.5*	8 no. Manu A flush diffuser 450 mm diameter	38 no. 600×600 mm prismatic panels (CW)	None	8200 nadir 3100 from seated position	PD only
5. Office	$30.3 \times 5.6 \times 2.4$ Note emitters in central zone approx 20×5.6 *2.9*	4 no. Manu A flush diffuser 450 mm diameter	30 no. 600×600 mm small cell louvre (WW)	4 no. 1.2×1.5 at ends of building. Sill height 0.8 White vertical Venetian blinds	2500 nadir 4800 from seated position	Individual luminaire control by downward facing cell
6. Office (3 no.)	(a) $6.7 \times 5.8 \times 2.7$ (b) $6.7 \times 4.2 \times 2.7$ (c) $6.5 \times 3.3 \times 2.7$ *(a) 1.6* *(b) 1.4* *(c) 1.3*	2 no. Manu A domed diffuser 450 mm diameter in each office	600×600 mm mirrored louvred downlight 9,9,3 no. (W)	None	(a) 1600 nadir 1100 from seated position, (b) 400/950 nadir 650 from seated position, (c) Not measured	None
7. School	(a) $9.0 \times 6.0 \times 3.0$ (b) $14 \times 10 \times 3.0$ (*a*) *1.6* (*b*) *3.5*	(a) 6 no. Manu B flush diffuser 300 mm diameter. (b) 4 no. Manu B 600×600	(a) 13 no. recessed CF downlight. (b) 12 no. 600×600 mm prismatic panels (CW)	(a) None. (b) Partial glazing on two sides 2.0×9.0 no. blinds	(a) 2400 nadir 1600 from seated position. (b) 400/900 nadir 300/600 from seated position	None

8. Office	20 × 9.0 × 2.5 3.7	5 no. Manu B 600 × 600	28 no. 600 × 600 mm mirrored louvred	None ‘Internal window’ to adjacent office	5000 nadir 2000 from seated position	PD only
9. Conference room	6.4 × 9.5 × 2.9 *1.8*	2 no. Manu B 600 × 600	12 no. Saturn ring white 21 cm diameter (24w)	No windows but internal glass block window 4 m × 2 m	25900 nadir 52 16 from seated position	None
10. Office	22.2 × 9.5 × 2.6 *3.7*	6 no. Manu A Hush diffuser 600 × 600.	38 no. 600 × 600 mm small cell louvres	3 no. 1.4 × 5.1 no. 1.4 × 4 No blinds	7000 nadir 3000 from seated position	None
11. Office	18.5 × 10.4 × 2.4 *2.1*	3 no. Manu B 600 × 600	6 no. 1200 mm mirrored louvred twin (WWT8)	None	4200 nadir 2000 from seated position	None
12. Workshop	20 × 10.4 × 6.5 *1.2*	11 no. Manu B domed diffuser 500 mm diameter	8 no. Glass prism industrial downlight	None but loading bay door open	ASK M	None
13. Office	11.9 × 11.6 × 2.8 *2.9*	9 no. Manu B 600 × 600	30 no. 600 × 600 mm small cell louvre (W)	None	13,000 nadir 10,500 from seated position	None

[a] Manufacturers denoted ‘Manu A’ and ‘Manu B’.
[b] All venitian blinds were adjusted to be open.
[c] Electrical lighting control on–off only unless stated.

Fig. 1. Exterior and interior views of two installations.

3.2. Achieved lighting levels

In their normal state, all buildings were lit by electric light supplemented by the daylight systems. Table 5 summarises the arithmetic average of the measured workstation illuminance values from combined electric lighting and daylight, and due to daylight alone, together with the appropriate unobstructed external illuminance. The summary of the statistics relating to all measured workstation illuminance values in Table 6 shows a very wide range for both total and daylight only values. However analysis of this data shows the illuminance for installations with windows not to be statistically significantly different from those without. Only 7% of the total occupants were working below the SLL recommended values for offices (300–500 lux), but some 75% were working in illuminance values above this range [9]. It could be argued that the majority of installations are over-lit in their working state and that the daylight systems are contributing to this.

Only 20% of the measured daylight levels would on their own satisfy SLL illuminance requirements for offices. In general, the daylight contribution represents between 25% and 50% of total illuminance. A major reason for this is that the number of luminaires exceeds the number of daylight output devices in all installations, in some cases greatly so. Also there is a big difference between the light outputs of the luminaires and the daylight output devices. The most common type of luminaire used – 600 mm × 600 mm downlight with four PL lamps has a typical light output of 4800 lumens. The daylight output of the devices in installation 4, for example, ranges from approximately 950 lumens in prevailing temperate overcast conditions to 8500 lumens under a midsummer clear-sky with sunlight.

Table 5
Summary of lighting levels in the installations

Building	Average illuminance across all workstations (lux)		Daylight apertures as % of wall or ceiling		Average external illuminance (lux)	Average work-plane DP/DPF (%)	
	Electric and daylight	Daylight only	Windows	Guide output		Measured	Estimated
1.1	600	Not measured	17	1.9	11,300		
1.2	930	211			23,000	0.9	1.1
2.1	570	Not measured	16	1.4	11,300		
2.2	846	410			35,000	1.1	1.1
3.1	760	42	0	0.9	7500		
3.2	1250	504			100,000	0.5	0.5
4.1	398	Not measured	0	0.7	10,000		
4.2	564	Not measured			95,000		0.4
5	607	Not measured	8	0.6	10,000		0.3[b]
6	531[a]	Not measured	0	0.8	10,000		0.44
7	220[a]	50	0	0.9	14,500	0.4	0.6
8	640	Not measured	0	1.0	10,000		0.3
9	794	477	0	2.0	92,000	0.5	0.53
10	624	Not measured	13	0.01	30,500		1.2
11	499	Not measured	0	1.4	28,000		0.41
12	1227	Not measured	0	1.0	85,000		0.7
13	700	Not measured	0	2.3	86,000		0.8

[a] Refers to room a in each installation.
[b] Not including contribution from windows.

Table 6
Summary statistics relating to the individual measured workstation illuminance values (lux)

	Mean	Minimum	1st Quartile	Median	3rd Quartile	Maximum
Electric and daylight	682	170	499	602	851	1500
Daylight only	283	36	117	310	413	715

Examination of likely daylight illuminance levels during working hours in the UK suggests that, for most of the year, each daylight device provides less than half the light output of the luminaires used.

The daylight contribution is shown in Table 5, first as the area of glazing aperture as a percentage of the relevant wall or ceiling area and, second, the daylight contribution expressed in terms of daylight factor and/or daylight penetration factor. In some installations, the daylight contribution was measured, but in others this was not possible. For installations having both windows and light guides, the value quoted is the sum of DF or DPF for each light source. There is a strong statistically significant relationship ($P < 0.01$) between daylight aperture areas and DF/DPF. The outliers in this relationship are installations where the guide lengths are optically long resulting in transmission losses and reduced light outputs. In general, although the total window areas are small compared with, say, those of a typical office building, they are some 10 times that of the daylight output devices. Despite this, the windows deliver less daylight. For installation 2, for example, measurements in an adjacent empty room of similar size and containing identical lighting equipment showed that the guide output devices deliver some 85% of the daylight.

A seasonal increase in daylight contribution was evident in the four installations visited twice. In each, the total workstation illuminance increased by approximately one third, but, as noted above, no mechanism existed to substitute this for electric lighting.

4. Comparison of prediction with measurement

Since the purpose of the comparison was to assess tools suitable for practising designers, the semi-empirical methods were excluded from this exercise. The measured data were taken from all five installations where daylight measurement was possible, and from the three others with the largest guide apertures. Installations 1, 2 and 9 had small areas of vertical glazing, and the guide configurations of installations 7, 9 and 11 had large aspect-ratios and included bends.

The results in Table 7 show average values of DFP/DF at the work-plane level assuming a maintenance factor of unity. Good agreement between the methods occurred. This suggests that all are capable of producing results to a precision acceptable in practice; DF usually being specified to one significant figure. Ease of use of the methods however varies. Whilst assembly of data is a time consuming preliminary to all of the methods, the CIE hand-calculation method takes significantly less time than the two computer-based procedures. If analysis of an installation with significant areas of conventional windows was desired, or if individual point values of the DPF rather than an average were required, then the Liverpool software based method is recommended.

5. Discussion

All of the installations were effectively electric lighting supplemented by daylight guidance. They gave a wide range of workstation illuminances through working hours, the majority being above the SLL recommendations for offices and all were above the threshold conditions. None was used without electric lighting. Daylight generally provided between 25% and 50% of the total illuminance because the difference in number, and 'installed load', of the daylight providers in relation to the electric luminaires. The lack of daylight-linked control meant that diurnal variation increased the illuminance above the electric lighting design values. Although this permitted temporal illuminance variation, it prevented energy saving being realised even in summer conditions when daylight was capable of providing more than the SLL recommendations, but in no in-

Table 7
Comparison of measurement and prediction of average work plane DPF/DF

Building	Measured	SkyVision	CIE method	Liverpool/software
1	0.90	0.89	0.89	0.99
2	0.90	0.89	0.79	0.84
3	0.50	0.64	0.42	0.41
4	–	0.39	0.36	0.30
7	0.35	0.28	0.43	0.42
9	0.50	0.59	0.39	0.52
11	–	0.52	0.45	0.46
13	–	0.57	0.54	0.55

stances did switch off occur in these circumstances. Daylight/daylight penetration factors were generally below 2%, i.e. not enough to create an impression of a 'well lit' space using conventional fenestration [9]. The spatial illuminance variation achieved is dependent on the source configuration; the most common being regular arrays of luminaires and guide output devices together with small windows. This gave horizontal illuminance diversities across all buildings within the 5:1 maximum:minimum deemed satisfactory for electric lighting [9].

Any metric used for daylight-guidance installations must be compatible with that for DF since many installations are in buildings containing windows. DF is usually defined in relation to an overcast sky and is specified in the form a work plane average or distribution, the latter implying calculations for discrete points. To be compatible with DF, any DPF prediction method must therefore be calculated assuming an overcast sky: in which case, the two are additive.

No work has been done to date to establish values of DPF that give desirable conditions of quantity or distribution of daylight delivered by guides. This will require studies of user reaction to real or simulated daylight-guidance systems. Until results of work of this nature are available, it is not possible to make definite statements about design criteria. However anecdotal evidence during the surveys suggested that users regarded the spaces as being lit by electric lighting. This implies that DPF of the order of 0.5–1.0 is insufficient to create the feeling of a 'daylit space'.

The methods of prediction compared in this paper produce results that are in good agreement with each other and measured values. The ease of use of the methods suggests that all three could be regarded as a potential design tool for a practitioner. A number of issues do however require attention. The first relates to assumptions about sky conditions (luminance distribution and global illuminance) embodied in the models. Whilst intuitively a designer would use the sky model most appropriate to the location, the evidence is that, in most cases, the luminance distribution is not as important as global illuminance at the collector in calculating the DPF. It could however be important using short guides in locations with predominantly high sun-angles. This work used a unity maintenance factor. This was to aid comparison but also because no maintenance factor has been collected in the short history of guide systems. These data are required for use in practice to enable comparisons to be made between guidance systems and other forms of natural and electric lighting. Finally, there is the question of accuracy of both measurement and prediction methods. The authors of the methods do not state measurement tolerances. Given the vagaries of daylight, these are however unlikely to differ from those of the installation surveys described in this work, that is ±10%.

6. Conclusion

Tubular daylight guidance systems were conceived some 15 years ago and are now installed in a large number of building types worldwide. This paper suggests that suitable metrics exist for quantitative analyses of the systems, that suitable prediction methods are available for designers but that robust design criteria to enable the systems to be specified or evaluated have yet to be developed. Because of the emerging nature of the technology, it will be some time before designers can have the same confidence in their use as with conventional natural and electric lighting systems.

Acknowledgements

David Carter is Chair of the Commission Internationale de I'Eclairage Technical Committee 3-38 'Tubular daylight-guidance systems' and acknowledges the help of members of this committee in the preparation of this paper.

References

[1] Jenkins D, Muneer T. Modelling light-guide performances – a natural dayiighting solution. Build Environ 2003;38:965–72.
[2] Jenkins D, Muneer T. Light-pipe prediction methods. Appl Energ 2004;79:77–86.
[3] Zhang X, Muneer T. A design guide for the performance assessment of solar light guide. Light Res Technol 2002;34(2):149–69.
[4] Laouadi A, Galasiu A, Atif M, Haqqani A. Skyvision: a software tool to calculate the optical characteristics and daylighting performance of skylights. In: 8th International BPSA conference, Eindhoven, Netherlands; 2003. p. 705–12. Available from: <http://irc.nrc-cnrc.gc.ca/ie/light/skyvision/>.
[5] Carter DJ. The measured and predicted performances of passive solar light-guide systems. Light Res Technol 2002;34(1):39–52.
[6] Chartered Institution of Building Services Engineers. The calculation and use of utilisation factors. Technical Memoranda 5. London: Chartered Institution of Building Services Engineers; 1980.
[7] Illuminating Engineering Society. The calculation of utilization factors – the BZ method. IES Technical Report 2, London; 1971.
[8] Lumen Micro 2000 users guide. Boulder (USA): Lighting Technologies Inc.; 2000.
[9] Code for interior lighting. London: Society of Light and Lighting; 2004.